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THE CERENKOV FREE-ELECTRON LASER

FINAL REPORT

John E. Walsh

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U.S. Army Research Office

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The primary focus of the research supported by this contract was the evaluation of compact free-electron laser concepts. Two types of device were examined in detail. The first, a Cerenkov Free-Electron Laser (C-FEL), used a dielectric-film-loaded, quasi-optical resonator to couple the driving electron beam with the radiation field. In the second type of device, a metal grating was used as the coupling element. The latter source is called a Metal-Grating Free-Electron Laser (MG-FEL), or Planar Orotron. In either case, the designation *compact* was quantitatively defined by the relation between the operating wavelength and the energy of the driving electron beam. The C-FEL tuning was shown to scale with the product of the film thickness and the relative energy of the electron beam ($\lambda \sim d \cdot \gamma$), while in the MG-

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19. ABSTRACT (cont.)

FEL, the grating period becomes the small scale parameter. The scale length is typically small compared to the operating wavelength, and much smaller than a typical undulator period. Thus, sources in this class do not require extraordinary electron beam energy to reach short operating wavelengths. A second scaling relation which followed from a coupling constraint was also established. Acceptable gain strength (defined by achievable resonator Q) and the acceptable efficiency was defined by the size of ratio of the beam thickness σ and the product of the wavelength, the relative velocity, and the relative energy of a beam electron ($2\pi\sigma/\lambda\beta\gamma$). These two scaling relations were used as design guides in wide range of experiments.

The C-FEL was operated with three types of beam generator: a high-voltage pulse transformer (100-250 KV), a Marx generator (550 KV - 1.1 MV), and a small RF-driven circular accelerator (5 MV). The wavelength range explored covered the region between 100 μm and 10 mm where the shorter wavelengths were achieved with the higher energy electron beams. To date, only the first two types of beam generator have been used to drive the MG-FEL, which has been operated over the 1- to 10 mm-wavelength range. Wavelengths in the 1.5 to 2 mm region were achieved with only 7 KV beam voltage. in the middle- to longer-mm region and at higher drive, the voltage (10-50 KV) MG-FEL parameters (1-15% single-pass, untapered efficiency and 20% fractional tuning range) compete favorably with existing sources. At submm wavelengths, it appears that they could be operated in a CW mode. The details of the experiments and theory required for its interpretation were presented in 30 publications. The bibliography and abstracts are included in the report.

An outline of a general theory which may be used to compare C/MG-FEL performance to each other and to other conceptual schemes was developed. A summary of this work is also included with the report.

1. Introduction

The work completed with the support provided by this contract has been summarized in the six semi-annual progress reports, in the manuscripts which have been submitted to journals, and in the theses which have been prepared. Copies of the published materials have been forwarded as they have become available and copies of the longer thesis documents are made available to anyone on request. Presented here is a brief summary of the principal results obtained and comments on the potential future development of Cerenkov and Metal-Grating Free-Electron Lasers (C- and MG-FEL's). Included with this report is a list of degree recipients whose work has benefitted from the support of this contract, a bibliography of the published work, and copies of the abstracts of the principal published contributions.

The main focus of the program has been on experiments which, in the broader context, were aimed toward providing compact, coherent, tunable source in the submm and far-infrared regions of the spectrum. Results of these experiments are well summarized in the published work. In addition, in order to fully evaluate all source concepts on an equal basis, it was necessary to construct a general linear and nonlinear theory. The general viewpoint is a recent development, and it has not yet been published. Hence an outline is included with this report (Appendix A1).

2. Summary of Major Achievements

A brief summary of the principal results obtained with the support of this contract will be presented in this section. The discussion will be subdivided into subsections on experiment and theory, and the subsection on experiment will be further subdivided by resonator type (C-FEL or MG-FEL).

2.1. Summary: Cerenkov Free-Electron Laser Experiments

In the Cerenkov free-electron laser experiments, dielectric-loaded quasi-optic resonators were used to couple the electron beam to the electromagnetic field. Three types of electron beam generators were employed: a pulse-transformer-based modulator (which operates in the 50-250 KV range), a Marx generator (which operated in the 500 kv - 1.1 MV range), and a circular RF accelerator (microtron) operating at 5 Mev.

The pulse-transformer-based system was used primarily for mm-wavelength experiments. On the fundamental branch (TM_{01}) of a cylindrical shell-loaded guide, operation between 30 and 150 Ghz was obtained. A single resonator will typically tune over a 20-30 percent range and the electronic efficiency peaked near the lower end of the tuning curve for a fixed resonator geometry. The magnitude of the efficiency at wavelengths near 3 mm was typically 4-6%. Operation on TM_{02} at lower efficiency (0.1-1%) was used to extend the operating range above 300 Ghz (350 Ghz typical). However, efficiencies were obtained on occasion. Overall, the moderate-beam-voltage driven C-FEL is a simple, robust source of mm- and near-mm-wavelength radiation. Its principle disadvantage is the requirement for very careful beam focussing since any substantial charging of the dielectric liner will disrupt the beam flow.

The Marx generator-driven C-FEL can be operated over a range extending from the cm (S-band) through the longer part of the FIR (375 μm). In the series of experiments supported by this contract, the principal focus was on the submm-FIR region. Tuning over the entire 150-300 Ghz range was obtained with only two cylindrical shell-lined waveguide resonators (Garate *et al.*, Appl. Phys. Lett. 48(20), 1326, 1986), and tuning over the range 375 μm to 1 mm was achieved with a pair of planar film-loaded resonators) (Garate *et al..*, Nucl. Instruments and Methods A259, 128 (1987)). As was the case in the longer-wavelength experiments, the efficiency peaked toward the longer-wavelength end of the tuning range, reaching the 1% range near 1 mm. Sources of this type (Marx generator-driven) are a useful means of producing high-power, short-pulse, bursts of submm-wavelength radiation. Similar devices operating at long wavelengths have been recently considered as potential sources of very intense (GW) microwave generators.

A third category of C-FEL employs an RF accelerator-produced beam as the driver. In these devices, thin film (2-10 μm polyethylene)-loaded trough guide resonators were driven with a 5 Mev microtron accelerator. The accelerator is located at the ENEA Frascati Laboratory (near Rome, Italy) and that group has contributed both the accelerator and all of the control engineering needed in order to make use of the beam. Resonators are designed, built, and cold-tested at Dartmouth. The collaboration allows us to use a beam generator which is ideally suited for experiments in the 10 μm to 100 μm-wavelength range and to work with a group with considerable experience in small accelerator development and operation. It would, of course, be more convenient to have the beam generator located at Dartmouth and plans for such a device are being formulated. In the interim, the ENEA group is pleased to cooperate with both C-FEL and MG-FEL experiments. To date, radiation at the lower and upper ends of the 200 μm-2mm range has been observed. The preliminary designs did not allow for adequate light collection while at the same time maintaining acceptable x-ray shielding. A new resonator chamber has been constructed and support will be sought for further experiments.

2.2 Summary: Metal-Grating Free-Electron Laser Experiments.

As implied by the name, in the metal-grating free-electron laser (MG-FEL) (which is also called the planar orotron) a grating is used to couple the beam to the fields. The basic operating principles are identical to that of the C-FEL. However, in some applications, the MG-FEL has the advantage of operating at a lower beam voltage. The MG-FEL experiments have employed two types of beam generator: a very compact, standard magnetron modulator (5-15 KV), and the pulse transformer-based system used in the Cerenkov experiments. The low voltage system has been operated up to 180 Ghz and with the 50 to 250 kv modulator operation, just below 300 Ghz has been achieved. At the longer end of the mm-wavelength region (5-10 mm) single resonators driven by the low voltage system have been tuned over a 25% range and untapered resonators have yielded efficiencies of about 5-7%. Tapering of the grating slot depth increases the efficiency but narrows the tuning range. Thus, in the mm and near-mm range, the low voltage MG-FEL is a potentially attractive souce for many applications. When operated at slightly higher voltage, it appears that submm-FIR operation of the MG-FEL is a realistic goal. Furthermore, unlike the C-FEL, charging is not a problem and CW operation is also possible. Hence it may be used as a source for spectroscopy (voltage-tuning and phase-locking are possible in principle). Plans for these experiments are being formulated.

2.3 Development of the Theory for C- and MG-FEL Operation.

The theoretical program carried out in parallel with the C- and MG-FEL development has been concentrated primarily on topics of direct concern to the experiment. Thus, the development of expressions for: operating wavelength, gain, sensitivity to beam quality, gain saturation, and efficiency have been emphasized. The theory necessary in order to design and interpret the experiment has been included in the publications, which have already been completed.

Recently, a very general theory for the evaluation of the potential of grating and film-coupled free-electron lasers has been developed. Poynting's theorem, in its complex form, has been used as an organizing framework within which all devices may be compared in a uniform manner. A general discussion of the design principles governing not only submm-FIR devices but the potential of MG- and C-FEL sources at shorter wavelengths is being prepared for publication. A copy will be forwarded as an appendix to a further proposal. Included here, presented in outline form, is a preview of this work(Appendix A1). The work was first displayed publicly at a colloquium presented at MIT Lincoln Laboratories on October 26, 1988.

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Personnel involved in the research who received ARO support during the Contract period:

G. Boudreaux, staff research assistant
T. Budka, research assistant, A.B. Senior Honors candidate
R. Cook, Research Engineer
E. Garate, postdoctoral research associate
E. Haber, research assistant, A.B. Senior Honors candidate
B. Johnson, graduate research assistant; Ph.D. candidate
M. Kimmitt, Visiting Scientist (University of Essex, England)
R. Layman, Senior Research Associate
E. Marshall, postdoctoral research associate
C. Shaughnessy, graduate research assistant; Ph.D. candidate
J. Walsh, Principal Investigator
Y. Xu, graduate research assistant; Ph.D. candidate

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A 100 μm Cerenkov Laser Experiment

J. Walsh, B. Johnson, C. Shaughnessy, F. Ciocci, G. Dattoli, A. DeAngelis, A. Dipace, E. Fiorentino, G.P. Gallerano, T. Letardi, A. Renieri and E. Sabio

Nucl. Instruments and Methods ***A250***, *308 (1986).*

The basic operating principles of far-infrared Cherenkov lasers are summarized and then used as a design guide for a proposed 100 μm region oscillator experiment. A discussion of the required accelerator and resonator parameters is presented and the preliminary experimental progress is reviewed.

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A Broadband Photon Drag Detector for Pulsed, High-Power Radiation Detection

E. Garate, R. Cook, C. Shaughnessy, G. Boudreaux and J. Walsh

International Journal of Infrared and Millimeter Waves 7(12), 1827 (1986).

A broadband detector based on the photon drag effects in semiconductors has been used for radiation detection from 600 mm to 1 cm wavelength. The measured responsivity of the detector at the longer wavelengths is ~ 3 μV/W.

A Review of Far-Infrared Free-Electron Laser Characteristics and Experiments

J. Walsh

SPIE 666 Far-Infrared Science and Technology 22 (1986)

A brief introduction to the theory of free-electron laser operation is presented. Emphasis is on summarizing the characteristics needed for operation in the 10-1000 μm region of the spectrum. A survey of current far-infrared free-electron laser experiments is also included.

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Novel Method for the Calculation of Cerenkov Free-Electron-Laser Gain

B. Johnson and J. Walsh

Phys. Rev. A 33(5), 3199 (1986)

Cerenkov free-electron-laser gain has been calculated in a number of ways by many authors. Often, the method employed depends upon the operational regime, either single-particle of collective. A technique is presented here which is largely regime independent and offers an intuitive picture of the stimulated emission mechanism. The technique employs the "averaged Lagrangian", and the reader is referred to Whitham for a more thorough discussion of that method.

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The Cerenkov Free-Electron Laser

J. Walsh, C. Shaughnessy, R. Layman, G. Dattoli, G.-P. Gallerano, A. Renieri

IEEE Proceedings of the IEDM CH2515, 13.1, 1987

Cerenkov radiation, produced by mild- to moderately-relativistic electron beams as they traverse dielectric-loaded surface wave resonators, can be used as the basis of a free-electron laser. Devices of this kind have now been operated at wavelengths ranging from the cm to the far-infrared region of the spectrum. Recent work is summarized in Table 1. Three different accelerator types and a range of operating voltages have been employed. Pulse-line accelerators (PLA) and pulse transformers (PT) have been used in the mm-submm regime. At shorter wavelengths, compact radio-frequency accelerators can be employed. In this summary, a review of 5 MeV microtron-accelerator-driven experiment will be presented.

Cerenkov Maser Operation at 1-2 mm Wavelengths

E. Garate, S. Moustaizis, J.M. Buzzi, C. Rouille, H. Lamain, J. Walsh and B. Johnson,

Appl. Phys. Lett. ***48(20)****, 1326 (1986)*

The interaction of a dense ($n \sim 10^{12}\ cm^{-3}$), mildly relativistic ($1.8 < \gamma < 3$) electron beam and a cylindrical, dielectric-lined waveguide has produced tunable microwave radiation in the 150-310 GHz frequency range with an estimated power output of 500 kW at 150 GHz and 10 kW at 310 GHz. The measured output frequency agrees well with the frequency for which the phase velocity of the TM_{01} mode of the dielectric-lined guide is synchronous with the electron beam velocity.

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A Comparison at Infrared Wavelengths of Metal-Grating and Dielectric-Film Free-Electron Lasers

P.M. Phillips, E.M. Marshall, J. Walsh and C. Shaughnessy

Proceeings of 12th Int. Conf. on IR & MM Waves, IEEE ***CH2490****, 63 (1988)*

A comparison of the tuning, gain, saturation, and beam-quality-related restrictions of metal-grating and dielectric-film free-electron lasers will be presented. While recent operation of the former has resulted in tunable radiation in the low-mm wavelength band, indications are that the device may readily be scaled to operate at submm, far-infrared, and possibly shorter wavelengths. For the latter, operation to date has been well into the FIR. These results, and an in-depth look at the prospects of the metal-grating FEL, will also be summarized.

Cherenkov Free-Electron Laser Operation from 375 to 1000 μm

E. Garate, C. Shaughnessy, B. Johnson, J. Walsh and S. Moustaizis

Nucl. Instruments and Methods A259, 125 (1987)

The first time operation of a far-infrared Cherenkov free-electron laser is reported. Continuously voltage-tunable radiation from 375 μm to 1 mm wavelengths has been produced from an electron-beam-driven slow-wave supporting structure consisting of two parallel metal plates covered with a thin dielectric film. A cold cathode field emission diode was used to generate the electron beam of density ~ 10^{12} cm^{-3} with a beam energy that varied between $2 < \gamma < 3$. The measured wavelength agrees well with the wavelength for which the TM_{01} mode phase velocity is synchronous with the electron beam velocity. The measured power output of the device indicates the production of 10 kW at 400 μm, 75 kW at 500 μm and 200 kW at 1 mm wavelengths, yielding conversion efficiencies up to 0.2%.

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Planar Orotrons: Recent Experiments, E. M. Marshall, P.M. Phillips

J. Walsh, D. Wortman, G. Hay, R. McMillan and D. Guillory

SPIE 791 Millimeter-Wave Technology IV and Radio-Frequency Power Sources, 13 (1987)

The planar orotron is a promising new device which is capable of producing millimeter and submillimeter radiation of moderate to high power. The orotron resonator is a slow wave structure consisting of a rectangular metal grating which is opposed by a planar metal boundary. When an electron beam grazes the grating surface, it can couple to travelling waves which then amplify and leave the resonator in the direction of the beam. For a given grating design, a unique and continuous set of frequencies may be represented by the travelling waves, making the planar orotron a remarkablly tunable source. Details of the theory of operation are presented, as are experimental results of one design which has produced up to 2 kW of power in the 30 to 40 GHz range using beam voltages under 20 kV.

High-Gain Free-Electron Laser at Far-Infrared Wavelengths

J. Walsh, E. Garate and C. Shaughnessy

*IEEE Journ. Quant. Elect. **QE-23(9)**, 1627 (1987)*

The small-signal gain is derived for a Cerenkov free-electron laser operating in the collective beam limit. The device consists of two dielectrically-lined parallel plates driven by a cold, relativistic electron beam. The dependence of the output wavelength on the resonator parameters and the electron beam energy is examined with particular attention devoted to device operation in the far-infrared and submillimeter portion of the electromagnetic spectrum at moderate electron beam energies ($\gamma < 3$).

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The Cerenkov Free-Electron Laser: A Critical Review and Progress Report

J. Walsh, C. Shaughnessy, B. Johnson, G. Dattoli, G.P. Gallerano and A. Renieri

***SPIE 738** Free-Electron Lasers, 70 (1987)*

Presented is a summary of the basic scaling relations which apply to Cerenkov free-electron-laser operation, together with a description of a 100 μm wavelength experiment currently in progress.

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Preliminary Results from a Microwave-Driven 100 μm Wavelength Cherenkov FEL Experiment

J. Walsh, C. Shaughnessy, R. Layman, G. Dattoli, G.-P. Gallerano and A. Renieri

*Nucl. Inst. Meth. **0499F**, 132 (1988)*

Radiation, with the characteristics expected of a Cherenkov signal, has been observed in an rf accelerator-driven, far-infrared Cherenkov laser experiment. The results of the first series of tests will be presented, together with brief descriptions of the major components of the system and a summary of the goals of the work.

Spontaneous Emission in Cerenkov FEL Devices: A Preliminary Theoretical Analysis

F. Ciocci, G. Dattoli, A. Doria, G. Schettini and A . Torre, and J. Walsh

*Il Nuovo Cimento **10D(1)**, 1 (1988)*

The main features of the spectral characteristics of the spontaneously-emitted Cerenkov light in circular and rectangular waveguides filled with dielectric are discussed. The characteristics of the radiation emitted by an electron beam moving near and parallel to the surface of a dielectric slab are also anlayzed. Finally, the relevance of these results to a possible FEL-Cerenkov operation is briefly discussed.

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Planar Orotron Experiments in the Millimeter-Wavelength Band

E.M. Marshall, P.M. Phillips and J. Walsh

*IEEE Trans. Plasma Science **16(2)**, 199 (1988)*

The planar orotron is a device which is capable of producing moderate to high power levels of millimeter and submillimeter wavelength radiation. The resonator is a slow-wave structure consisting of a rectangular metal grating which is opposed by a planar conducting boundary. The device operates in the surface harmonic mode: Electrons interact with axially-travelling waves which evanesce above the grating surface, and the amplified radiation leaves the resonator in parallel with the beam. Operation in both the forward and the backward mode is possible. The resonator cavity is designed to enhance longitudinal reflections, and thereby enhance the output power and efficiency. The output frequency and tuning range are determined by the grating parameters. Experiments performed in the backward mode have produced radiation from 30 to 110 GHz at power levels ranging from 100 W to 2 kW. The efficiencies vary from 1 to 7 percent. The measured frequencies are closely predicted by a theory which is also presented in this manuscript. Start currents are as low as 50 mA, and agree with calculated values in the cold-beam single-particle limit. The gratings may be scaled to opeated at higher frequencies, and techniques for doing so are presented and discussed.

APPENDIX A1: An outline of a general theory for Cerenkov and Metal-Grating FEL's.

The Cerenkov and Metal-Grating Free-Electron Lasers

M.I.T. Lincoln Laboratory
Lexington, MA

October 26, 1988

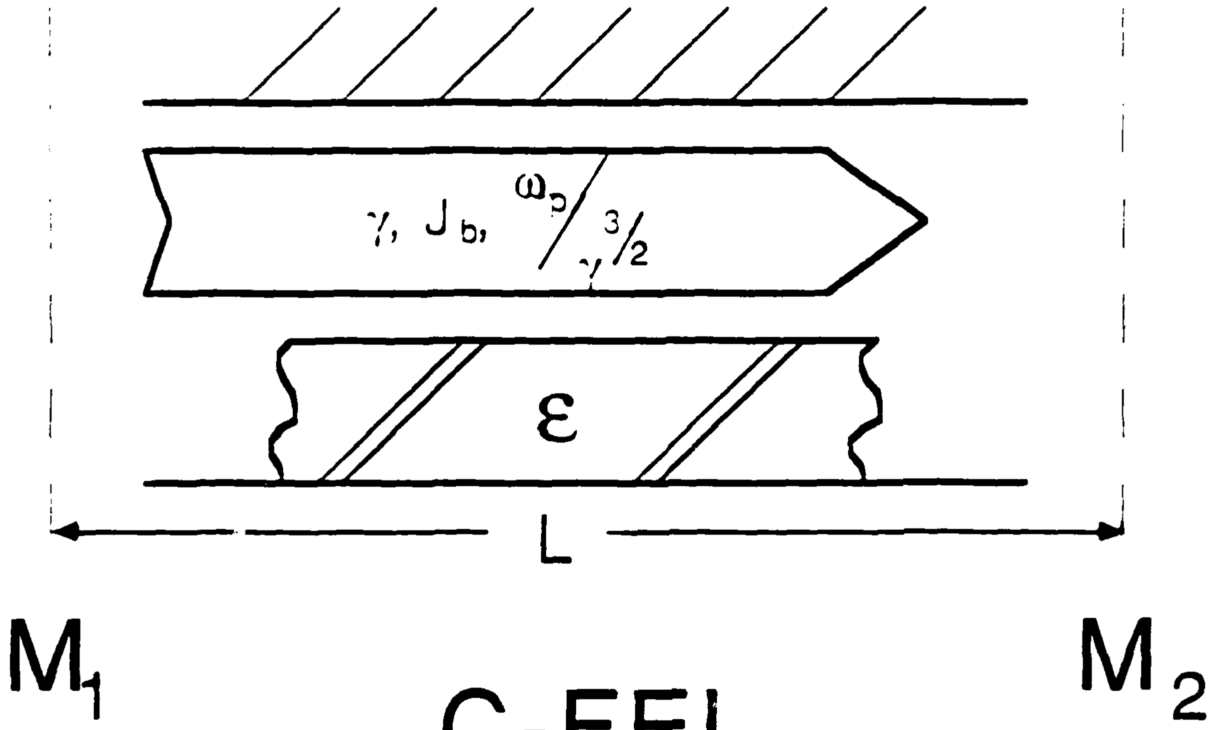
John Walsh
Department of Physics
& Astronomy
Dartmouth College
Hanover, N.H. 03755

INTRODUCTION

The outline of a universalization of the theory of Cerenkov and Metal-Grating free-electron lasers (C/MG-FEL) is presented in the attached figures and explanatory notes.

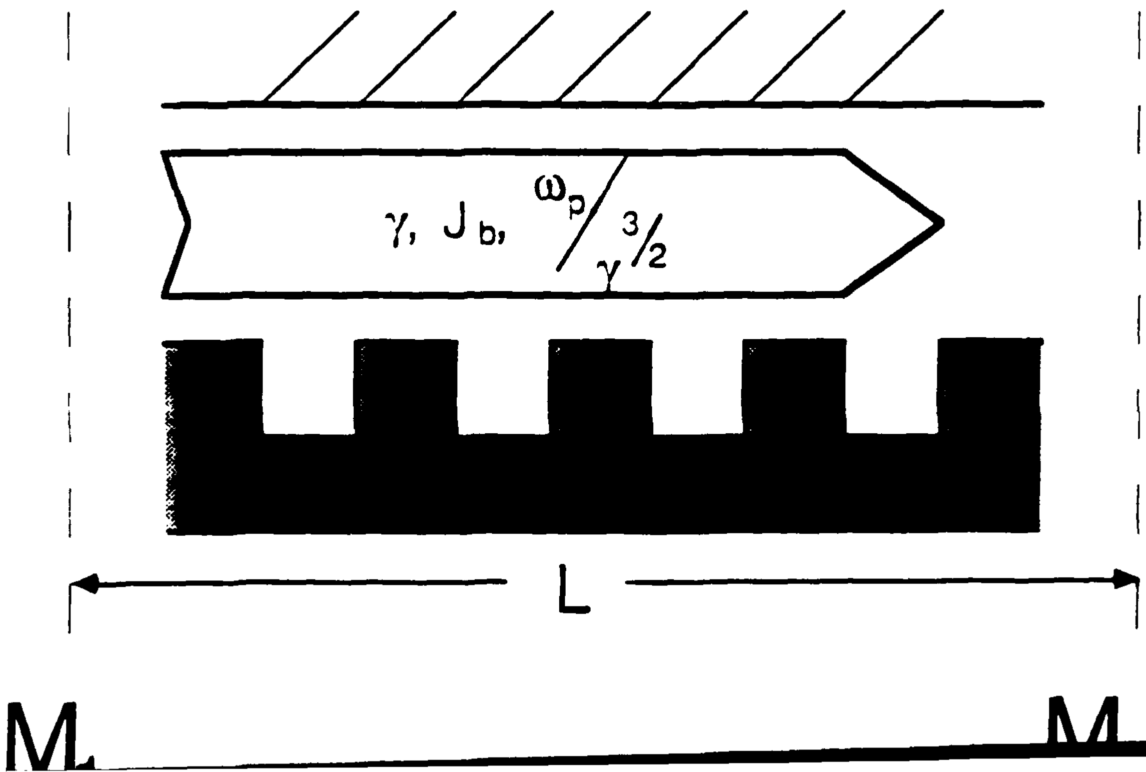
Since the basic theory underlying the operation of the dielectric-film-loaded (C-FEL) and the metal-grating-coupled (MG-FEL) devices are fundamentally the same, they are best discussed in parallel. In each case, the entering unmodulated driving electron beam is moving with a velocity which is close, but slightly greater, than the phase velocity of the forward propagating component of the resonator mode. Electron bunching occurs in the retarding phase of the wave and energy is transferred from the beam to the fields. The devices differ primarily in the way in which the subluminal phase velocity is achieved. In the first case (C-FEL), the dielectric slows the wave and in the second (MG-FEL), a grating is used for this purpose. Sketches are shown on the accompanying figure.

The essence of the coupling process is identical in both cases. When the beam energy and operating wavelength are fixed, the effective negative conductance created by the beam is, in fact, independent of the resonator structure. However, the overall coupling impedance does depend upon whether a film or a grating is used to slow the wave. Furthermore, in order to obtain good coupling with a C-FEL it is best to use beam energies which are at least mildly relativistic ($V_b > 100$ KV), and dielectric materials with a relatively low index of refraction ($n < 2$). The MG-FEL, on the other hand, remains a potentially interesting submm-FIR device even when driven with beams of quite modest voltage. In the case of the MG-FEL, the scaling arguments presented cna be used to define the conditions required for CW, submm and FIR operation.



$\gamma,\ J_b,\ \omega_p/\gamma^{3/2}$
ε
L
M_1
M_2

C-FEL



$\gamma,\ J_b,\ \omega_p/\gamma^{3/2}$
L

2. *SUMMARY OF THE BASIC C- AND MG-FEL THEORY*

The arguments presented are sorted into four components:

- **General Scaling Relations**
- **Tuning Characteristics**
- **Gain and Efficiency**
- **The Nonlinear Saturation**

Each major subsection is prefixed with explanatory notes.

BASIC SCALING RELATIONSHIPS

Three fundamental parameter groups may be used to determine the feasibility of operating C/MG-FEL at a given wavelength λ. when the relative energy of a beam electron, γ, the resonator length L , the beam current density J_b, and the energy spread $\delta\gamma$ are determined. These parameters are: the scale length set by the ratio of the beam current density, twice the number of wavelengths in the resonator, and the number of wavelengths in the length defined by the bem current density. The latter is measured in units of $\pi\ mc^3/e$ (π x 17 KA).

In each of the three cases, equality sets the margin of possible operation and this is the condition displayed on the three figures. The beam quality density and focus parameter choices on the figures are chosen in such a way as to range from "poor" to "good". Thus, the figures summarize the first of the basic design constraints.

Basic Scaling Relationships

$$\left(\frac{\pi I_o}{J_b}\right)^{1/2} \gtrless \frac{2L}{(\beta\gamma)^{3/2}}$$

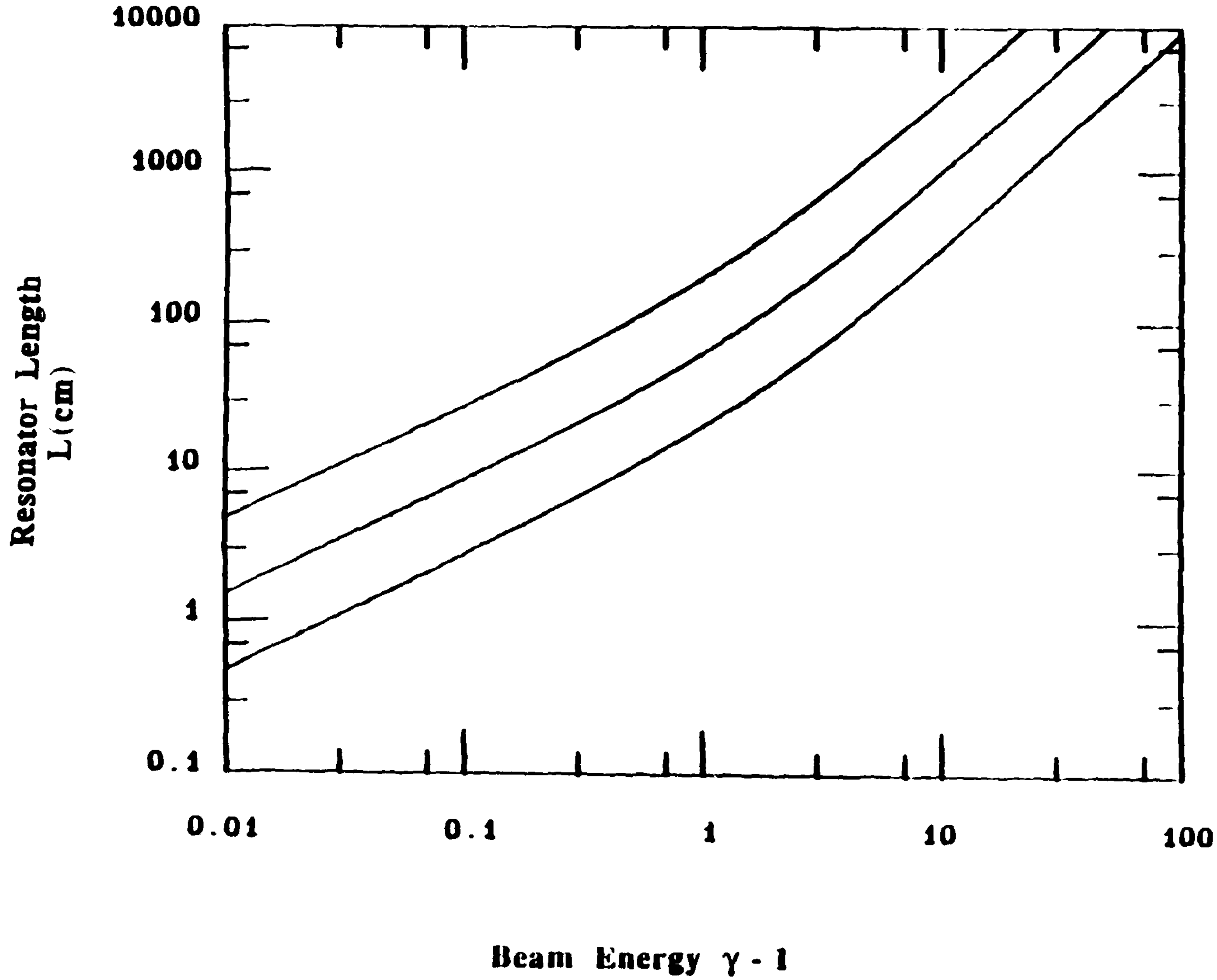
Compton/Collective Transition

$$\frac{\lambda}{2L} \gtrless \frac{\delta\gamma}{(\beta\gamma)^{3}} \qquad \textit{(Compton)}$$

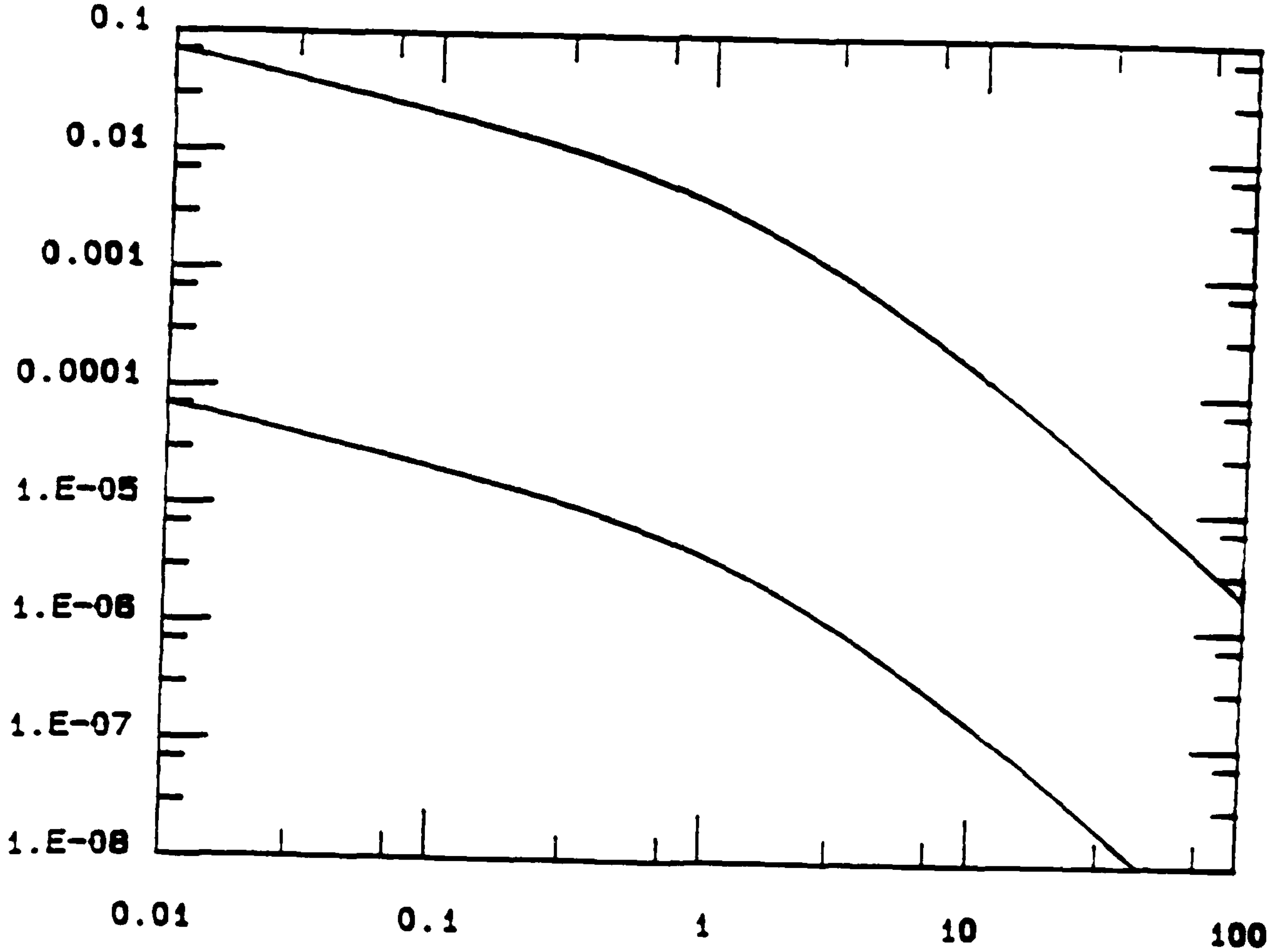
$$\frac{\lambda}{(\pi I_o/J_b)^{1/2}} \gtrless \frac{\delta\gamma}{(\beta\gamma)^{3/2}} \qquad \textit{(Collective)}$$

J_b - beam current density
I_o - 17.5 KA
L - cavity length
λ - operating wavelength
γ, β - relative energy & velocity of a beam electron

Resonator Length at Compton/Collective Crossover vs Beam Kinetic Energy



The Limiting Wavelength in the Compton Limit *vs* Beam Energy

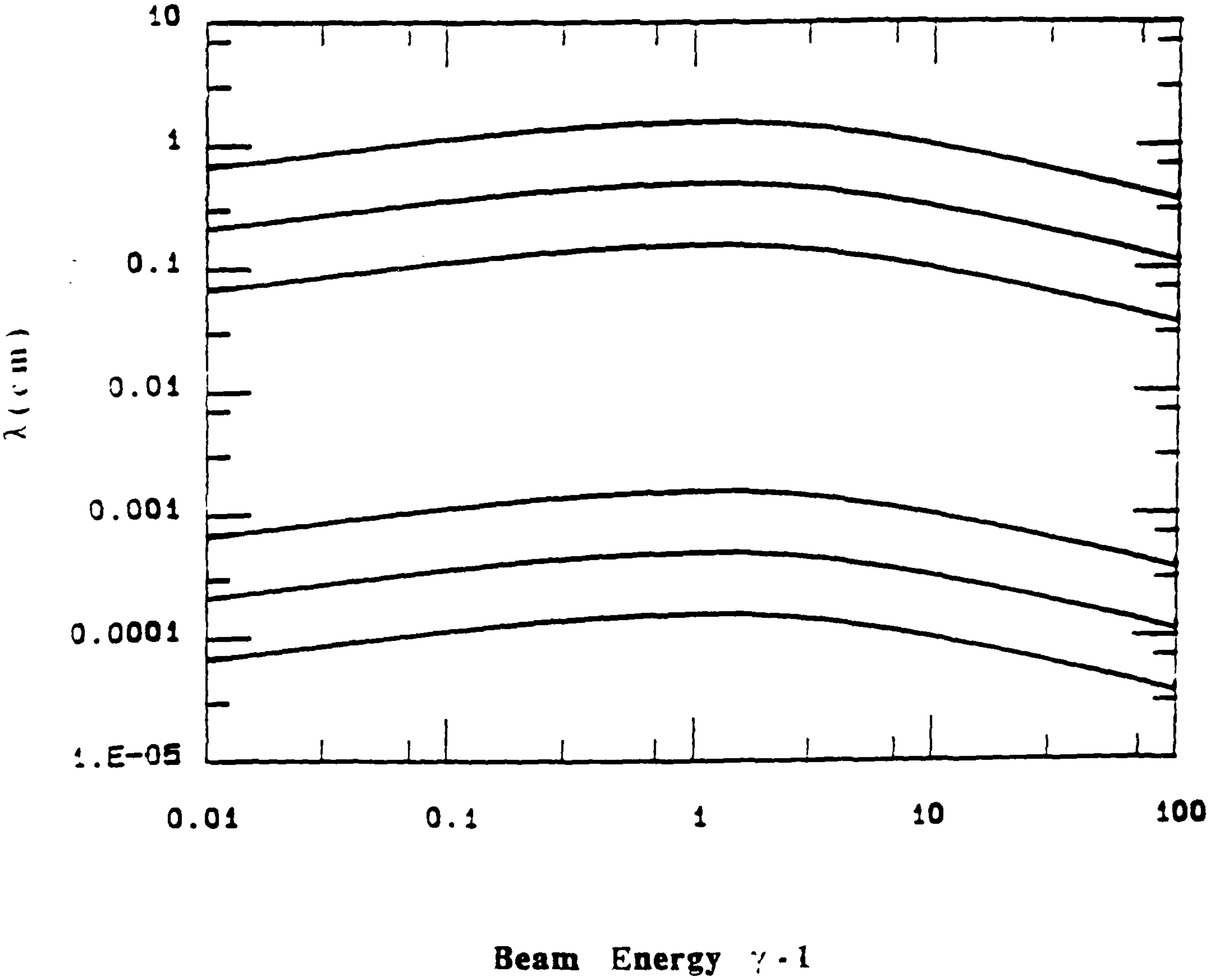


Beam Energy γ - 1

The Limiting Wavelength in the Collective Limit

$[\delta\gamma/\gamma{-}1 = 2 \times 10^{-2}$ *upper group,*

$= 2 \times 10^{-5}$ *lower group]*



TUNING CHARACTERISTICS

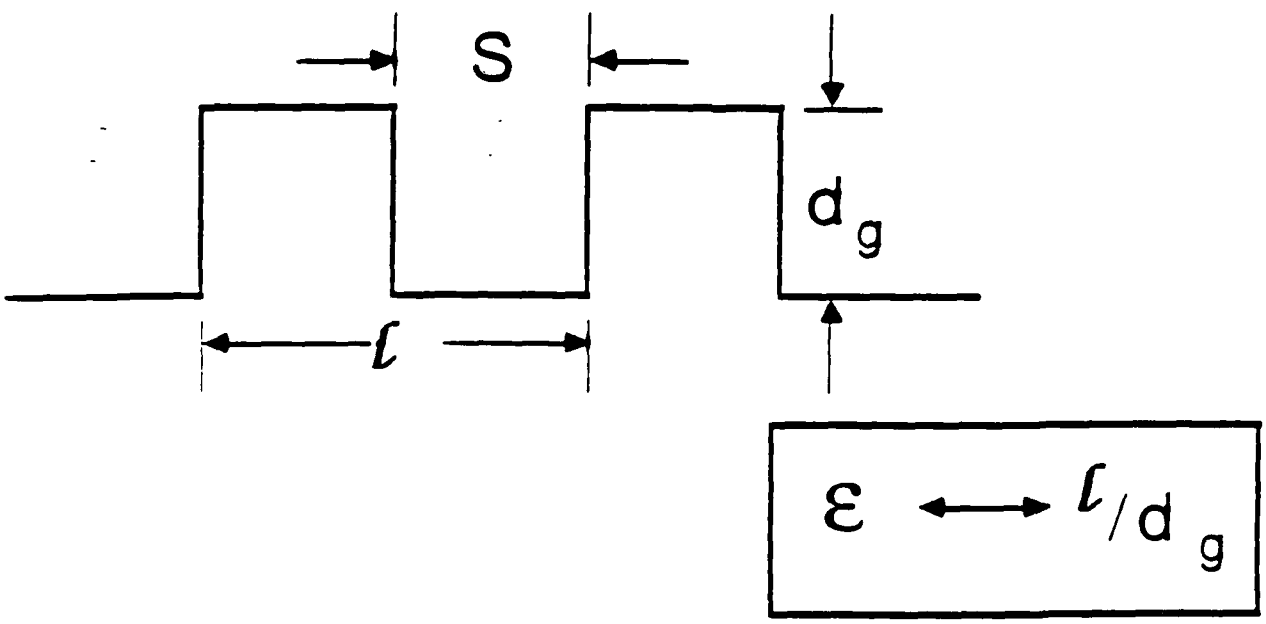
The tuning characteristics of a C/MG-FEL will depend on :

- **The film/grating parameters**
- **The dispersion relation**
- **Synchronism ($V_{phase} = V_{beam}$)**

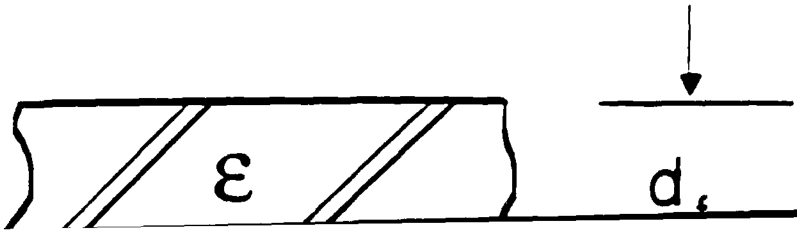
The film thickness and relative dielectric constant or the grating dimensions determine the boundary conditions for the appropriate solutios of Maxwell's equations. Together, the solution and the boundary conditions determine the dispersion relation for the resonator modes. The latter is a self-similar function of the dimensions and is thus conveniently displayed in dimensionless form. Sketches of the resonator details, typical dispersion curves, and tuning characteristics are displayed in the next four figures. The dispersion relation evaluated along a curve where the beam and phase velocities are synchronous, determines the tuning relation.

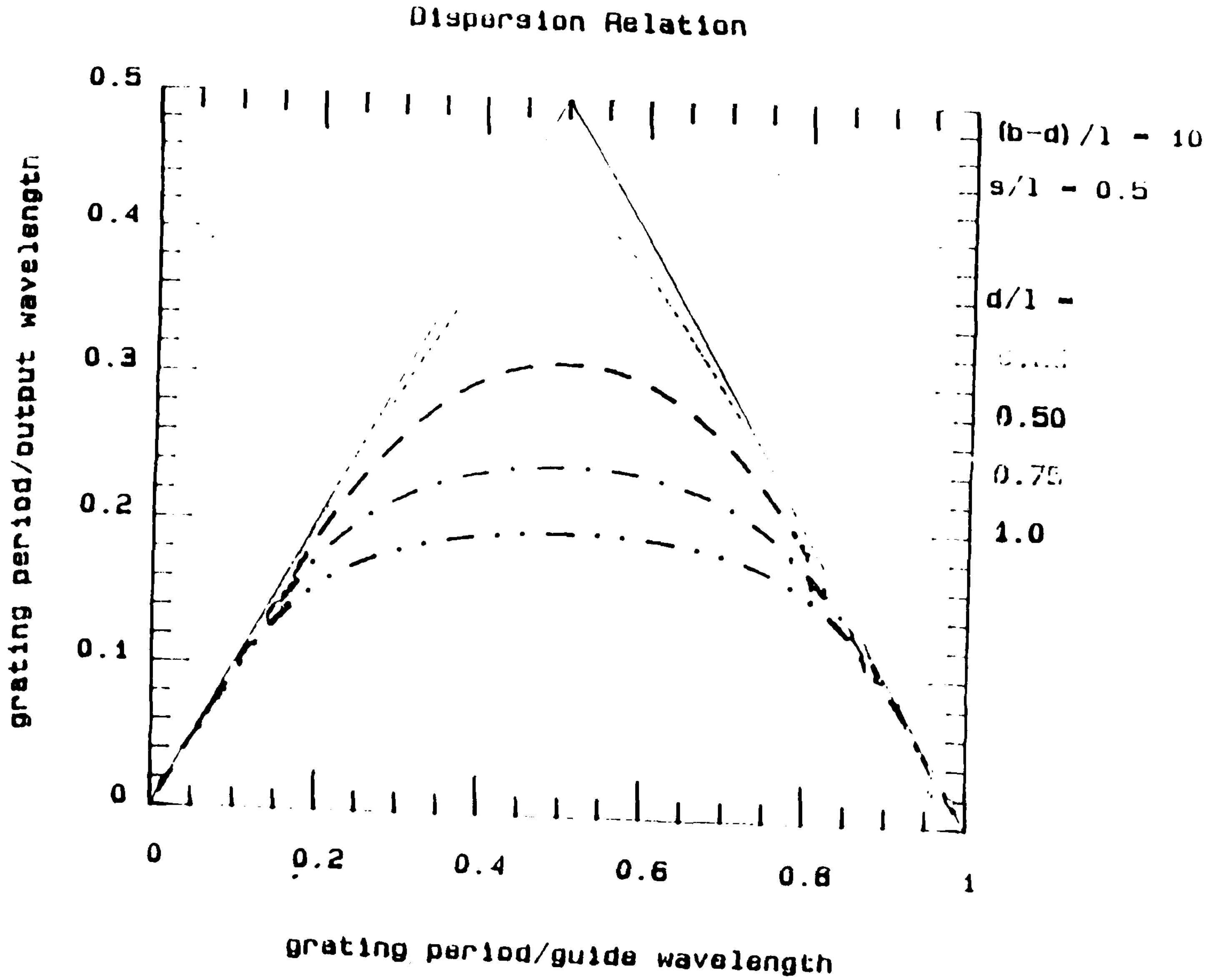
RESONATOR DIMENSIONS and the OPERATING WAVELENGTH

GRATING $\lambda = \lambda(\ell, \gamma, \ell/d_g)$

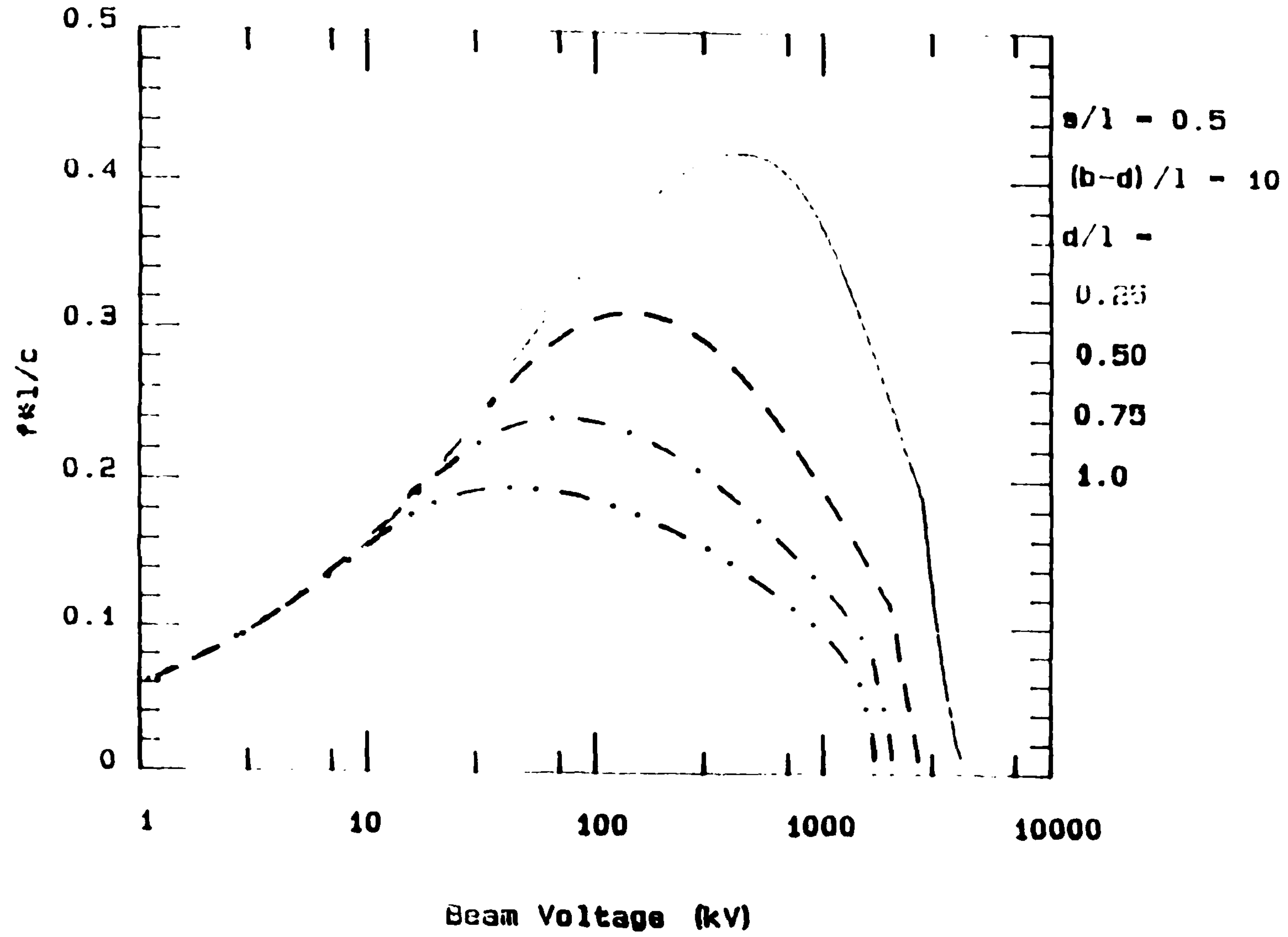


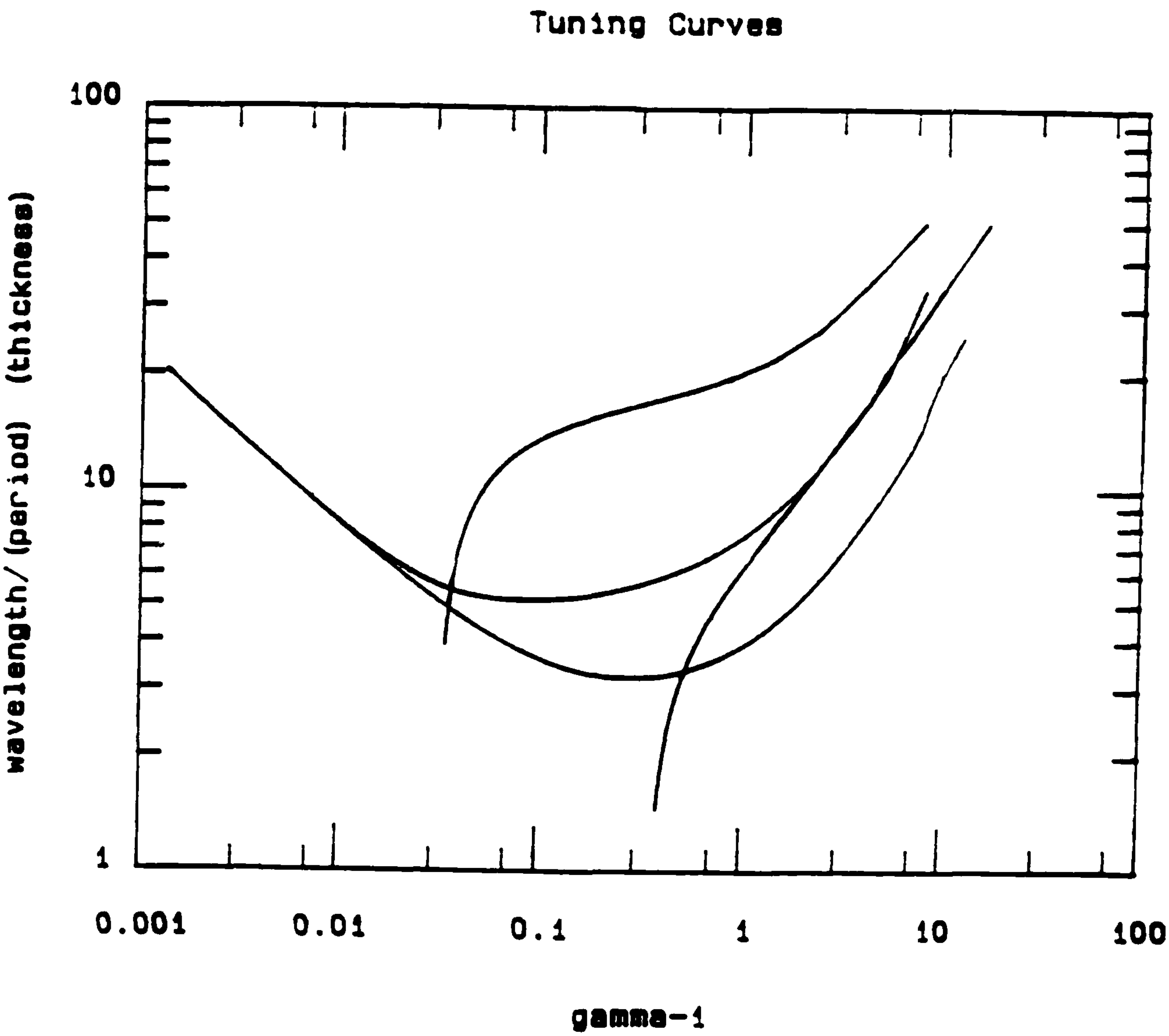
DIELECTRIC FILM $\lambda = \lambda(d, \gamma, \varepsilon)$




Dispersion Relation
grating period/output wavelength
grating period/guide wavelength
0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1
(b-d)/l = 10
s/l = 0.5
d/l =
0.50
0.75
1.0

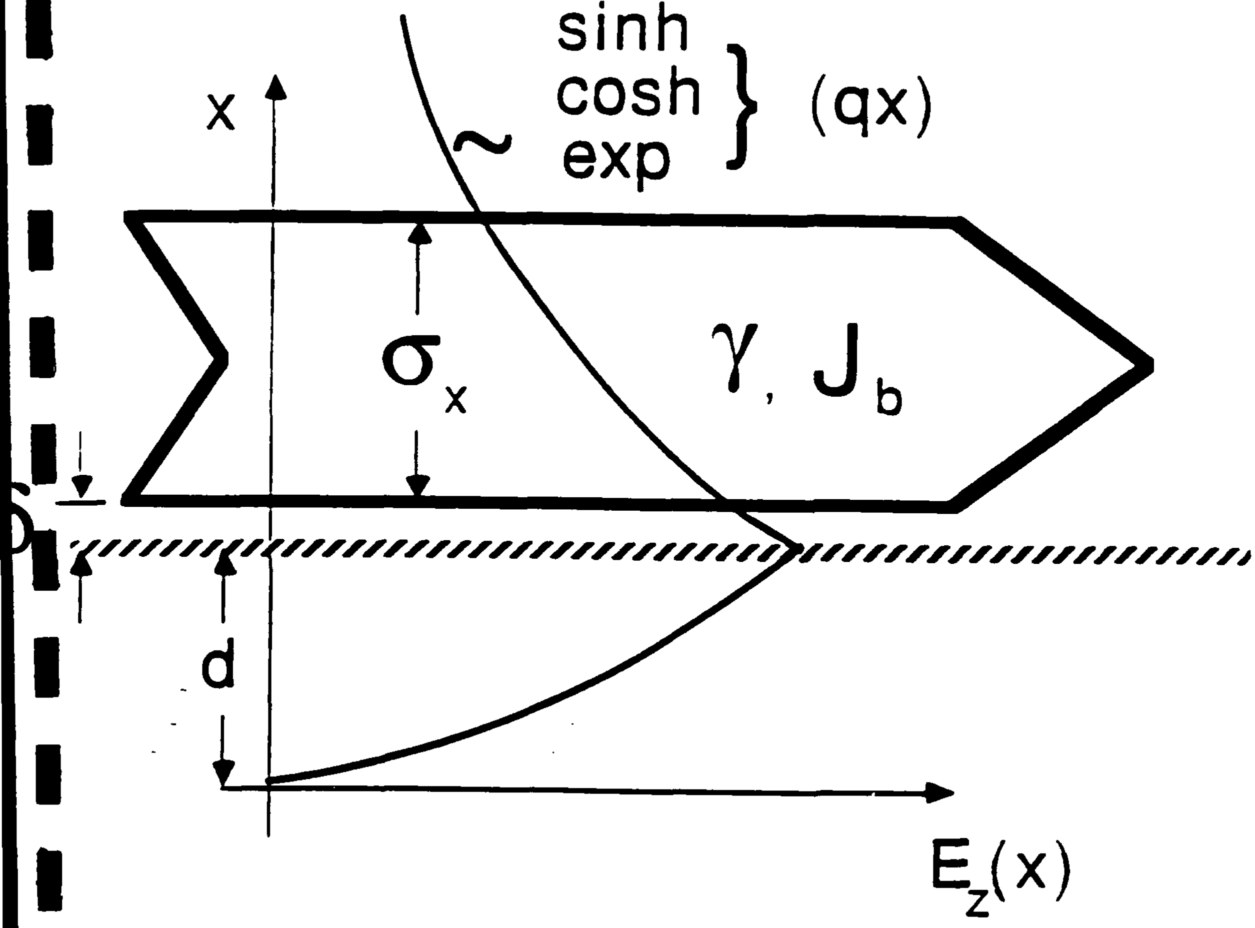
Universal Tuning Curves





Tuning Curves
100
10
1
wavelength/(period) (thickness)
0.001
0.01
0.1
1
10
100
gamma-1

COUPLING GEOMETRY



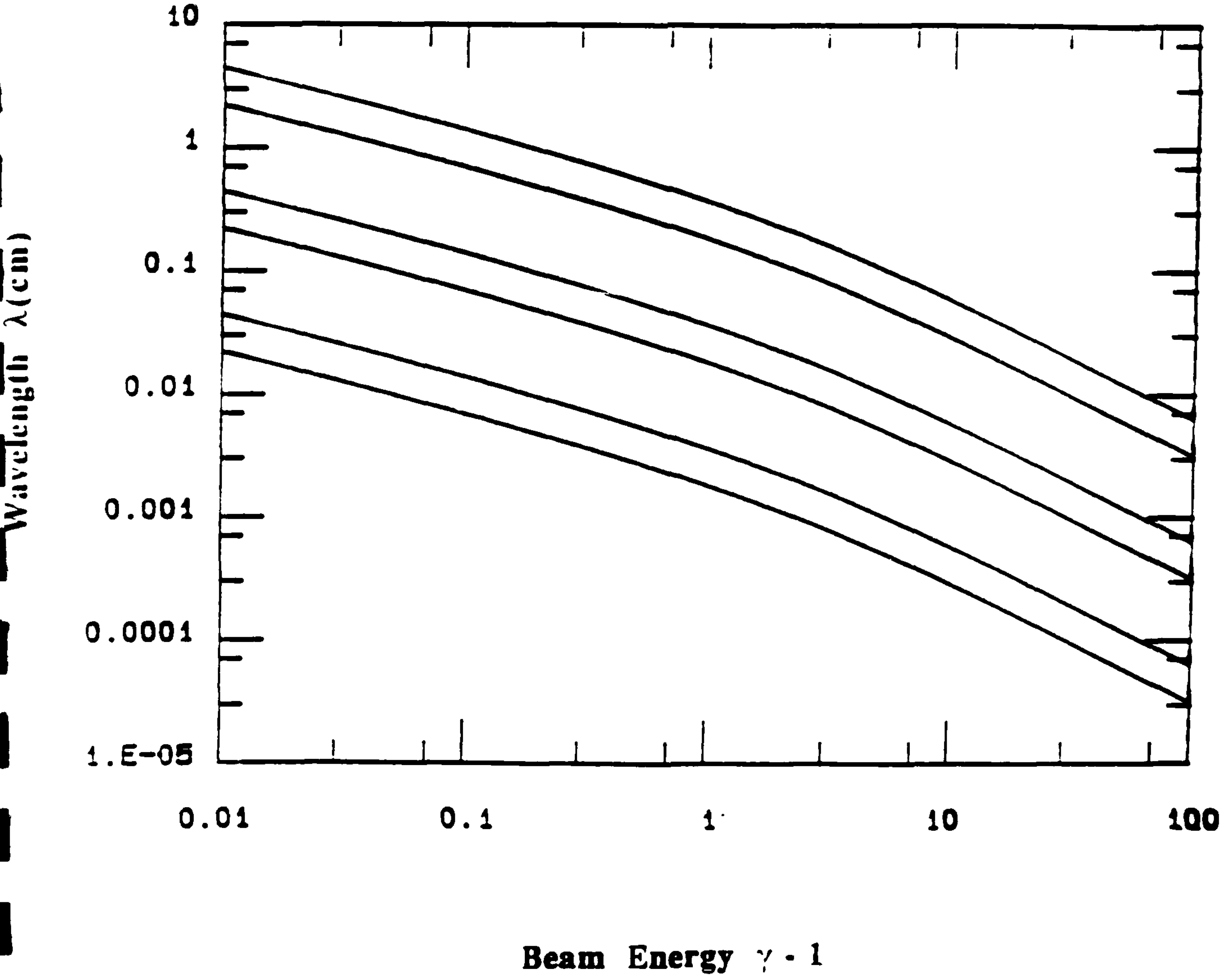
$$q = \sqrt{k^2 - \omega^2/c^2}$$

$$= k/\gamma \quad \text{(At synchronism } \omega = kv\text{)}$$

$$\mu_c = \frac{2\pi\sigma_x}{\lambda\beta}$$

The Critical Coupling Wavelength *vs* Beam Kinetic Energy

[σ_b = 0.1, 0.01, 0.001 upper, middle, lower groups, μ_c = 1.2 upper, lower]



Energy Storage and Power Flow

Poynting's theorem, in its complex form, is a convenient framework within which to discuss energy storage and power flow in an electron-beam-driven coherent radiation source. In the limit where the electromagnetic fields do not change appreciably during the time it takes a beam electron to traverse the interaction region, the theorem defines a discrete element equivalent circuit. The circuit elements so defined may be used to display the basic scaling characteristics of the source in question (tuning, gain, saturation, and sensitivity to beam quality).

The discrete element equivalent circuit in turn defines an ordinary differential equation which governs the time development of the resonator's mode amplitude. In the small-signal regime, the drive (beam admittance) terms defined by the theorem may be evaluated analytically and expressions for the growth rate and beam-related detuning displayed in closed form. As the wave amplitude grows, the nonlinear regime is reached and it is convenient to resort to a hybrid simulation technique. In this approach, the motion of typical beam particles are evaluated numerically and (entry-phase-averaged) numerically-defined nonlinear expressions for growth and frequency-shift obtained. These become the nonlinear coefficients in the now-also-nonlinear ordinary differential equation which governs the mode amplitude. Both the growth rate and the resonant frequency depend on amplitude and thus it is expected that a generic equation of the van der Pol/Duffing form would be a useful analytic description of these systems.

The hybrid simulation technique uses computation time economically and thus it is also a convenient means of examining questions such as the injection-locking range of a single oscillator or the parallel-locking parameters of a large array of identical sources. These features are sensitive to the nonlinear characteristics of the source and it is convenient to have a means of rapidly modeling this behavior. It is also important to note that the approach is not limited to weak beams since space-charge wave effects may be included in the definitions of the circuit elements. In a similar manner, it is also possible to inlcude beam self-fields when this is required.

When the change of the field amplitude during an electron transit time is not negligible, the circuit defined by the above approach consists of distributed elements. Devices such as the planar orotron, the Cerenkov maser, and other "long"-interaction-region sources may be modeled in this way. The distributed limit depends intrinsically on collective effects, while collective effects may or may not be important in the discrete limit.

The general relations are summarized on the next ten figures. Equations defining the basic parameters together with typical numerical results are both shown. It is apparent that the complex beam coupling is related to the resonator dimensions through the effective mode capacitance C and to the beam parameters through the conductance G. The gain relation is determined by the ratio $G/\omega C$ (i.e., the beam Q). Displayed in dimensionless form on the figures, it becomes the threshold value of Q when multiplied by the dimensionless perveance.

Energy Storage and Power Flow: 1

The Complex Poynting's Theorem:

$$i\,(\omega \mathcal{E}_E - \omega^* \mathcal{E}_M)$$

$$+ \int_{\text{beam}} \underline{J}^* \cdot \underline{E}\; dV$$

$$= \int_{\substack{\text{aperture}\\ \text{and losses}}} \underline{S} \cdot dA$$

$\mathcal{E}_{E,M}$ - the energy stored in the electric/magnetic fields

$\underline{J}$ - the (modulated) beam current

$\underline{E}$ - the electric field

$\underline{S}$ - Poynting flux

Energy Storage and Power Flow: 2

- $\mathcal{L} = 0 \;, \quad \underline{S} = 0$

$$\mathcal{E}_E(\omega,k) = \mathcal{E}_M(\omega,k)$$

- $J \neq 0$

$$\frac{1}{Q_b} \equiv \frac{1}{2}\,\frac{\int_{beam} \underline{J}^* \cdot \underline{E}\, dV}{\omega\, \mathcal{E}}$$

- ***Threshold***

$$\frac{1}{Q_b} + \frac{1}{Q_\ell} > 0$$

The Equivalent Circuit (Compton Limit)

$$i\left(\omega - \frac{\omega_{ok}{}^2}{\omega}\right) C(k,\omega)\ V$$

$$Y_b(k,\omega)\ V \quad = \quad Y_\ell(k,\omega)\ V$$

$$C(k,\omega) \quad \equiv \quad \frac{\int |E|^2\, dV}{8\pi\ V^2}$$

$$Y_b(k,\omega) \quad \equiv \quad \frac{\int \underline{J}^* \cdot \underline{E}\ dV}{V^2}$$

$$Y_\ell(k,\omega) \quad \equiv \quad \frac{\int \underline{S} \cdot dA}{V^2}$$

The Mode Capacitance

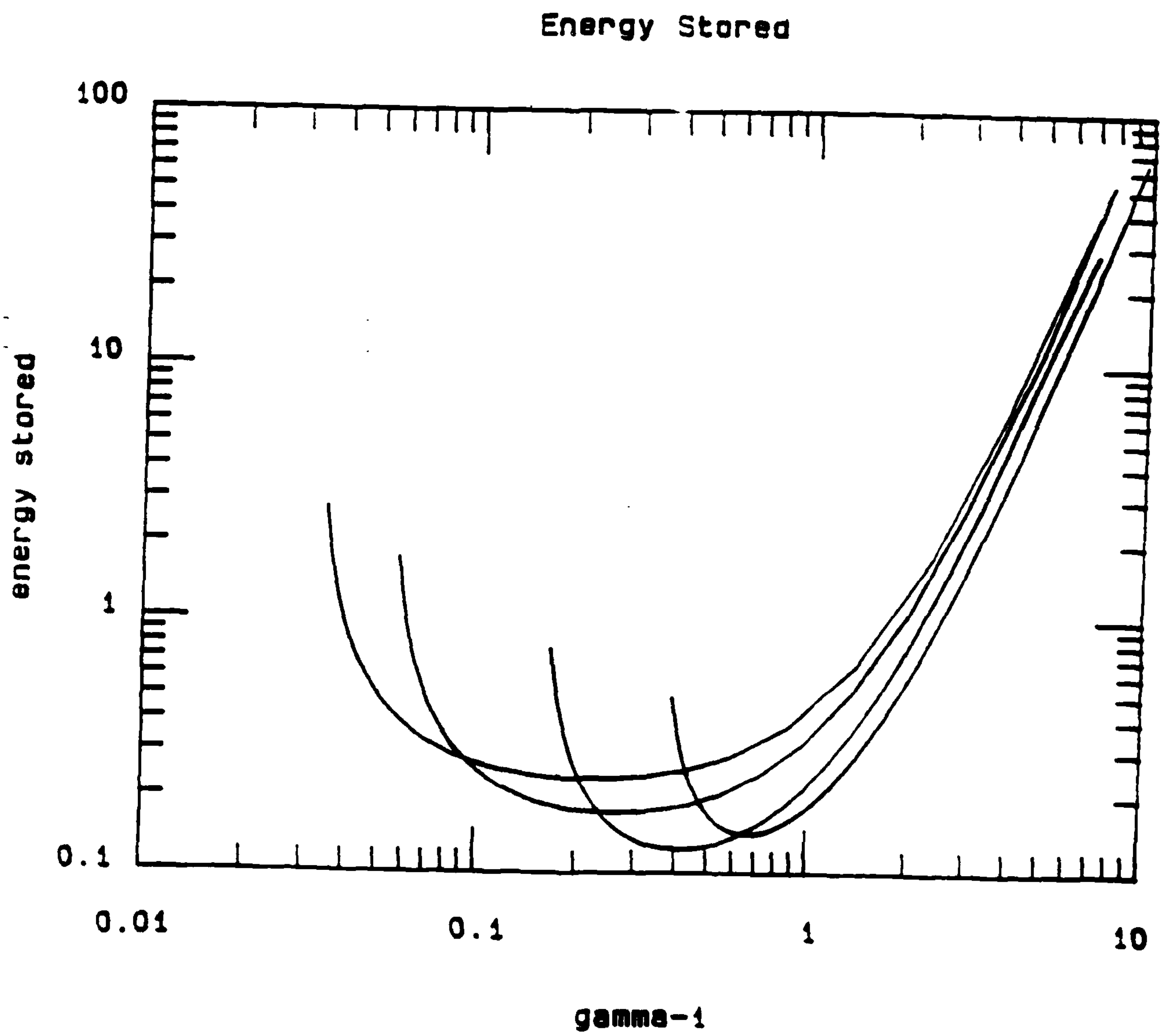
$$C(k,\omega) = \frac{w \cdot d}{L}\, \mathcal{C}\left(\frac{\omega d}{c} .\ kd\right)$$

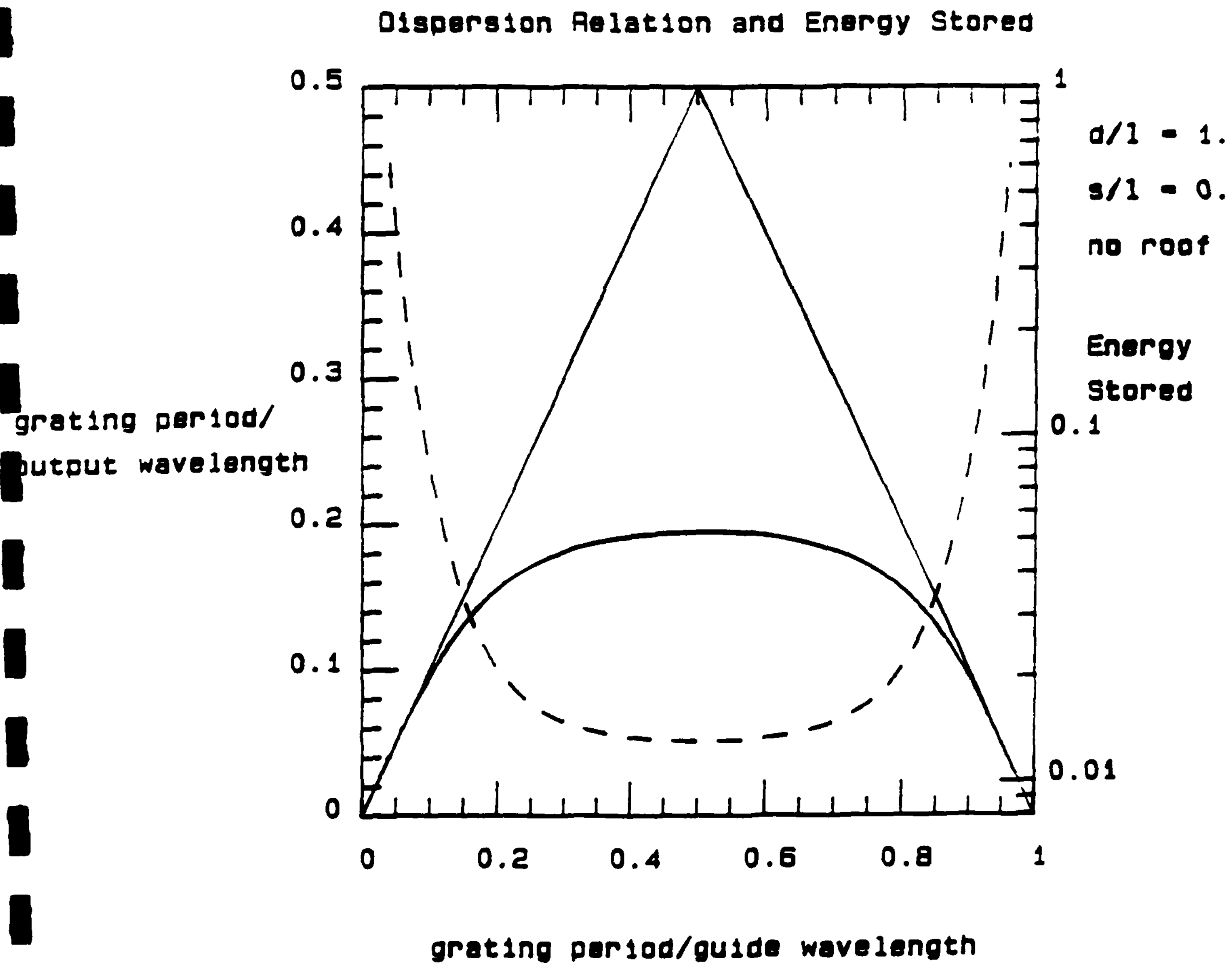
w - **mode width**

d - **scale length (film thickness, grating period)**

L - **resonator length**

$\mathcal{C}\left(\frac{\omega d}{c} .\ kd\right)$ - **dimensionless "capacitance"**


Energy Stored
100
10
1
0.1
energy stored
0.01
0.1
1
10
gamma-1


Dispersion Relation and Energy Stored
0.5
0.4
0.3
0.2
0.1
0
grating period/
output wavelength
1
0.1
0.01
d/l = 1.
s/l = 0.
no roof
Energy
Stored
0
0.2
0.4
0.6
0.8
1
grating period/guide wavelength

Beam Conductance (Compton Limit)

$$G_b \sim \frac{J_b}{(\beta\gamma)^3 I_o}$$ *perveance / cm²*

$$\times \frac{\int |E|^2 \, dA}{E_o^2}$$ *beam overlap (cm²)*

$$\times \quad \omega L$$

$$\times \quad F_R\left[\left(k - \frac{\omega}{v}\right) L\right]$$ *gain in line shape*

$$\omega L = kL \times v$$

(2π x # of guide wavelengths x beam velocity)

GAIN AND EFFICIENCY

The gain and efficiency depends essentially on two things:

- **The general constraints imposed by coupling**

and

- **the equations governing energy storage and power flow**

The first of these can be displayed in a general form, and this is shown on the following two figures. The transverse wave number in the beam channel when evaluated at synchronism is equal to the axial wave number divided by γ, the relative energy of a beam electron. This, together with the beam thickness, determines still another dimensionless group, designated μ_c. in general, efficient operation requires μ_c in therange 1-4. Examples are displayed on the figure.

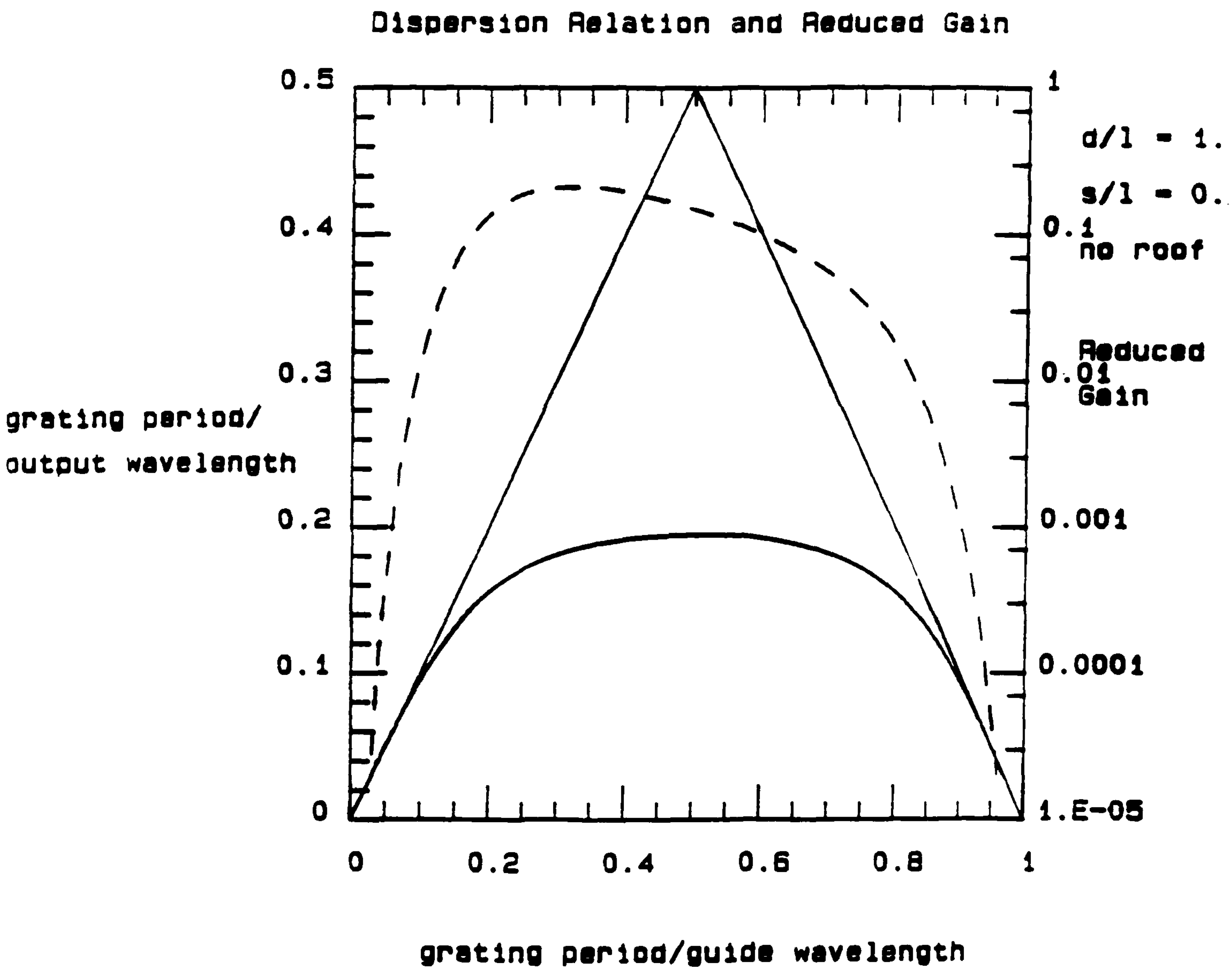
The Gain (Compton Limit)

$$\frac{1}{Q_b} = \frac{G_b(k,\omega)}{\omega C(k,\omega)}$$

$$g = \frac{L}{C(k,\omega)} \cdot \frac{G_b(k,\omega)}{v}$$

g - the gain-per-pass in the Compton limit

v - the beam velocity



Dispersion Relation and Reduced Gain
0.5
0.4
0.3
0.2
0.1
0
grating period/
output wavelength
1
0.1
0.01
0.001
0.0001
1.E-05
d/l = 1.
s/l = 0.
no roof
Reduced
Gain
0
0.2
0.4
0.6
0.8
1
grating period/guide wavelength

The Nonlinear Limit

The nonlinear saturation characteristics may be determined from an extension of the preceding arguments. As the field strength grows, a nonlinear expression for Q_b, valid at large amplitude, is defined by:

$$\frac{1}{Q_b(E_{ok})} \equiv \frac{\int \overline{\delta\gamma}(E_{ok})\, J_b\, dA \times (mc^2/e)}{\omega_{ok}\, \mathcal{E}\ (E_{ok})}$$

which determines the coefficients in the mode amplitude equation

$$\ddot{V}_k + R_e \left[\frac{1}{Q_b}\right] \dot{V}_k + \omega_{ok}^2 \left(1 + I_m\left[\frac{1}{Q_b}\right]\right) V_k = U$$

where

$$V_k = L\, E_{ok}(t)$$

This equation,when integrated numerically with the coefficients defined above, displays limit cycle behavior at saturation. The scaling of the saturation is displayed on the next figure.

SCALING OF THE FIRST SATURATION LEVEL

The relation:

$$\frac{\delta\gamma_s}{\gamma_o - 1} \simeq \frac{\gamma(\gamma+1)\lambda}{2L}$$

defines the energy change at the "trapping separatrix"

CONCLUSIONS

The foregoing outline is a general design guide which may be applied to any free-electron laser, although it has been displayed here in a form best suited to the discussion of C or MG-FEL's. The beam energy range chosen for the examples covers the region between: conventional microwave tubes (γ_o-1 = 0.01), compact accelerators (γ_o = 10), through to larger accelerators (γ_o = 100).
When the general relations defined are used together with either the operating parameters of existing beam generators or the target parameters of electron sources under development, the operating wavelength and efficiency may be determined.